

3D ALE-FEM for Microscale Two-Phase Flows

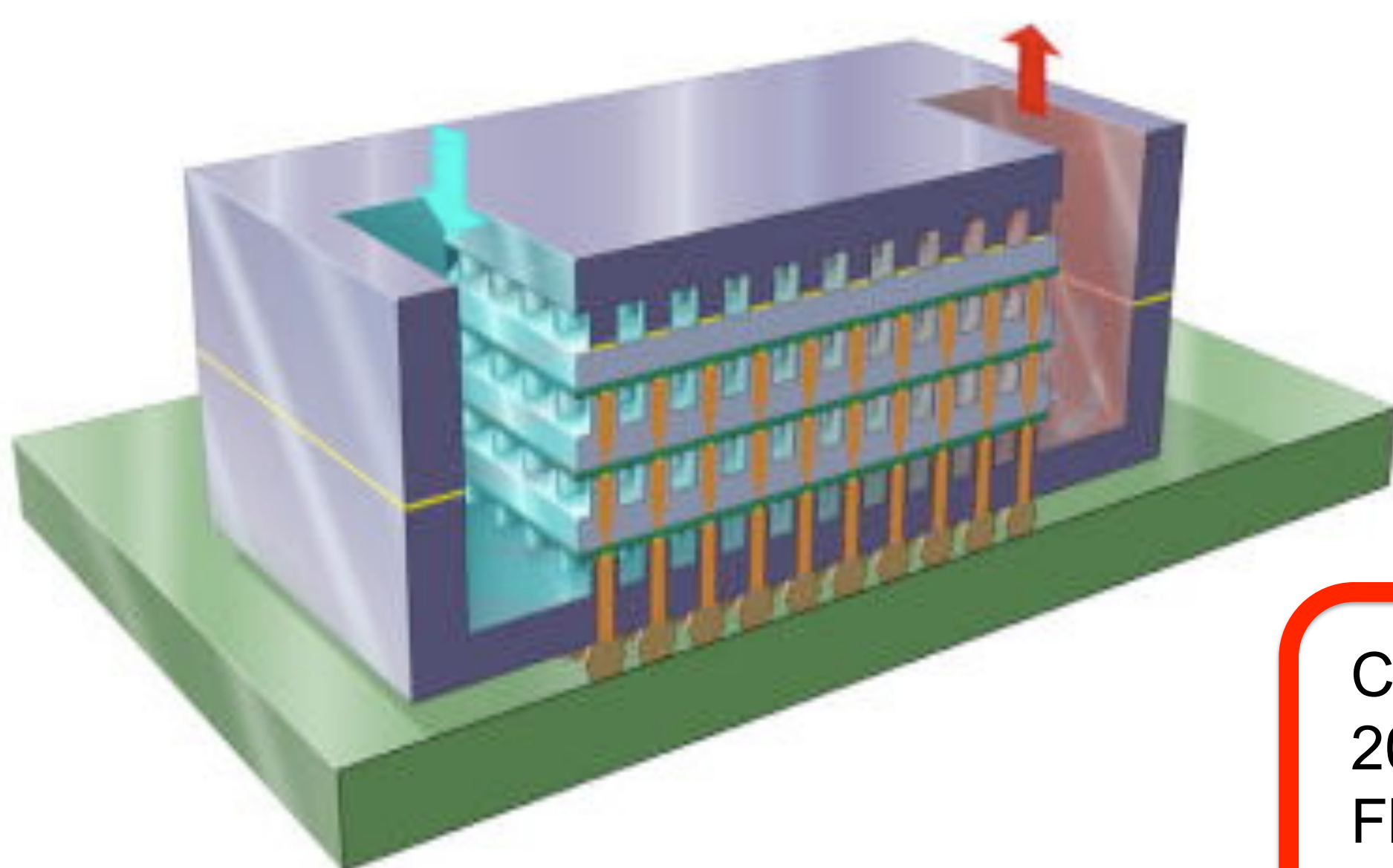
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1) Introduction:

The study of microscale two-phase flows is important in many areas of engineering. Since a full description of flow behavior in some situations is hard to predict experimentally, a numerical approach is often necessary to study particular cases. This work is part of the larger multi-disciplinary multi-laboratory CMOSAIC project which aims to study and design interlayer cooling system for the next generation of 3D stacked microprocessors, illustrated by:



Channel shapes:
Rectangular,
circular, square,
trapezoidal.

Channel sizes: 50µm to
200µm.
Fluids: water,
nanofluids, refrigerants

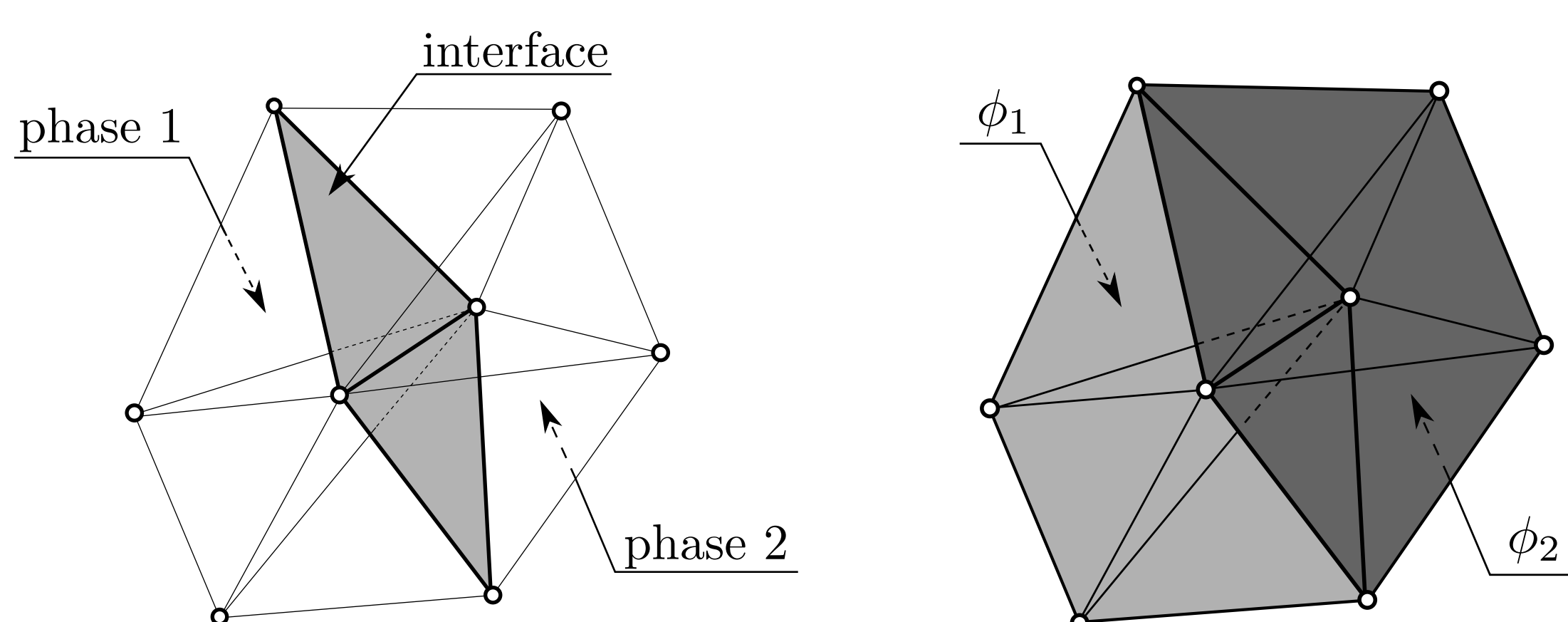
2) Objectives:

The goal of the present study is to:

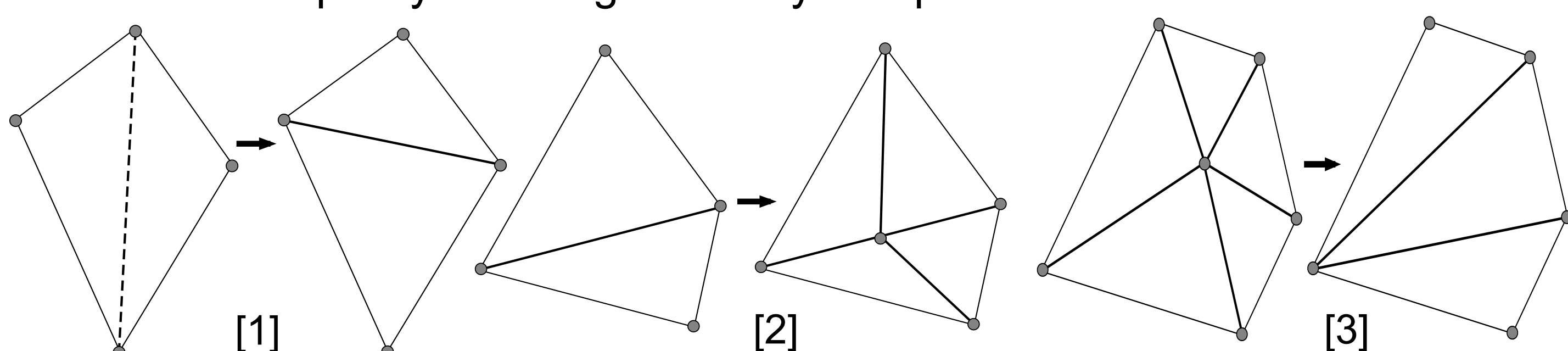
- Develop a 3D Arbitrary Lagrangian-Eulerian Finite Element code;
- Develop a platform for modeling two-phase flows;
- Predict flows in microscale geometries;
- Couple heat transfer and two-phase flow.

3) Surface Tension Force Model and Geometric Operations on the Interface:

Illustrated by the figure below, the Lagrangian approach differs from the standard approach by the addition of points on the surface between the fluids. In fact, no artificial smoothing is required to deal with high properties ratio (Φ_1/Φ_2). This methodology leads to a sharp representation of interface and accurate results.



Due to insertion of points on the surface, it is mandatory to treat the mesh properly to preserve the aspect ratio of elements. Flipping operation is done where two elements don't present good shape, thus the edge is swapped as shown in [1]. Insertion of points are performed where the edge become larger than a referential edge length [2]. Deletion of point occurs where the concentration of elements is saturated [3]. All the illustrated operations tends to keep the mesh in a reasonable quality ensuring accuracy and precision of calculation.



4) Arbitrary Lagrangian-Eulerian Framework:

Shown in dimensionless vector form, the Navier-Stokes equations analytically represents the fluid flow, where $\mathbf{u}, p$ and T represent the velocity, pressure and temperature fields respectively; ρ, μ, k and c_p stand for the density, the viscosity, thermal diffusivity and the specific heat of the phase Φ , Re, Fr and We are dimensionless parameters to characterize the flow regime; t is the time and g is the gravity. On the heat transport equation, $\mathbf{q}$ stands for the heat flux and H is the Heaviside function.

$$\rho c_p \frac{DT}{Dt} = \frac{1}{RePr} [\nabla \cdot k \nabla T + \dot{q} |\nabla H|]$$

$$\nabla \cdot \mathbf{u} = \left(1 - \frac{\rho_l}{\rho_v}\right) \dot{q} |\nabla H|$$

Mass transfer

$$\rho \frac{D\mathbf{u}}{Dt} = -\nabla p + \frac{1}{Re} \nabla \cdot [\mu (\nabla \mathbf{u} + \nabla \mathbf{u}^T)] + \frac{1}{Fr^2} \rho g + \frac{1}{We} \kappa \nabla H$$

mesh velocity gravity surface tension

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} - \hat{\mathbf{u}}) \cdot \nabla \mathbf{u} \quad \hat{\mathbf{u}} = \mathbf{u} \rightarrow \text{Lagrangian}$$

$$\hat{\mathbf{u}} = 0 \rightarrow \text{Eulerian}$$

5) 3-Dimensional Results:

Figure (4) shows the time progression of a Taylor air bubble immersed in a sucrose solution. In the transient evolution, the bubble's velocity reached its maximum velocity at time $t \approx 1$, and its terminal velocity at time $t \approx 3.7$. Also, it was shown that the bottom part of the bubble was pulled in and oscillated until convergence at $t \approx 7.4$. Figure (4) presents the transient solution of the bubble's center of mass velocity. The result agreed to the prediction of the flow pattern map, obtaining an error of 1.1%

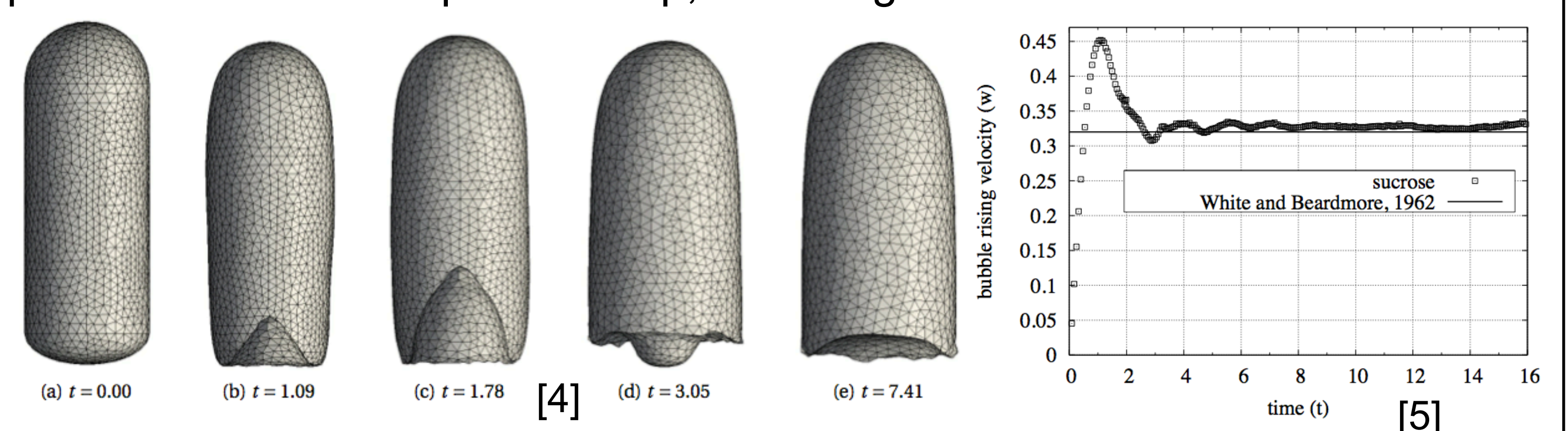
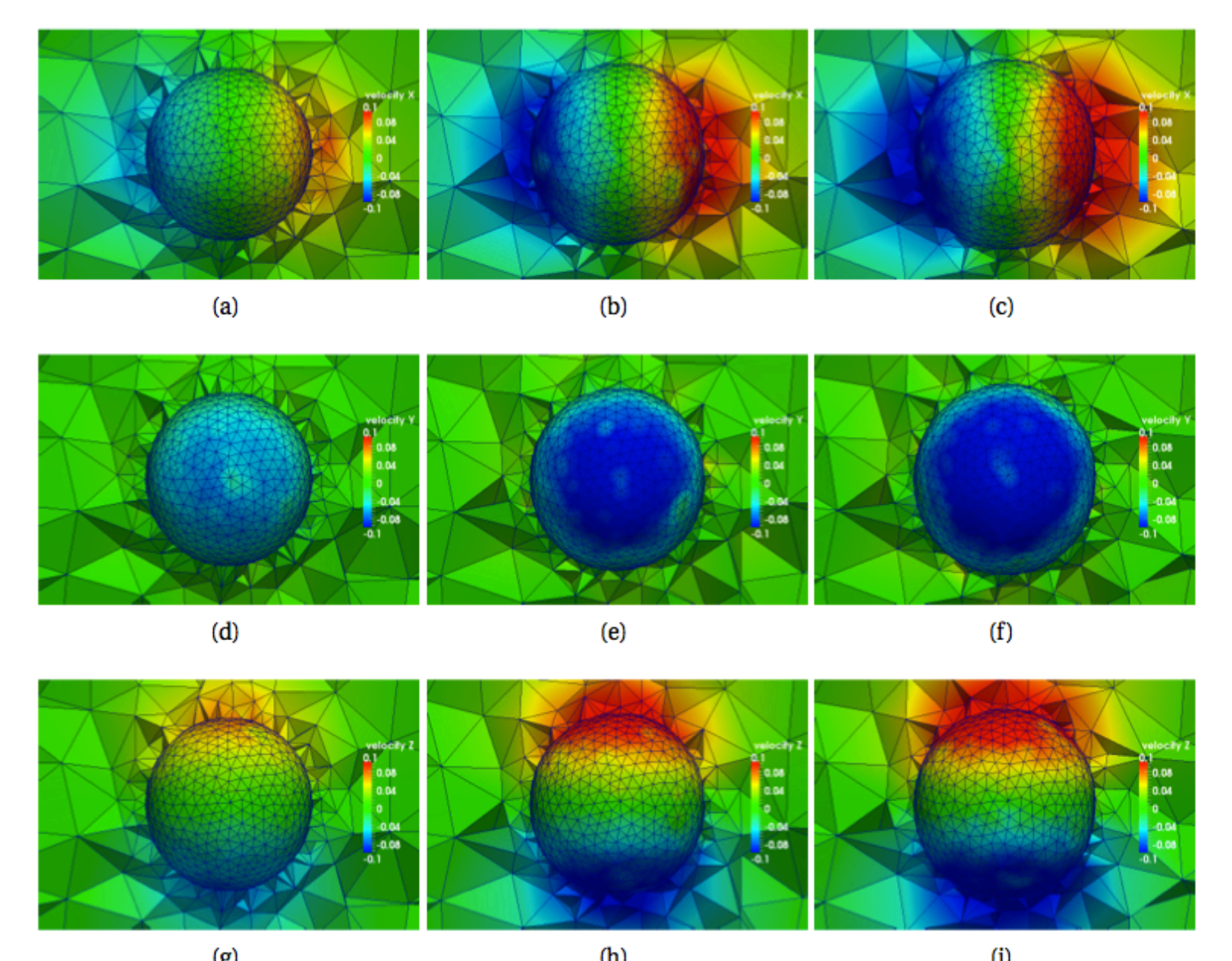


Figure (6) presents the velocity profile (u, v and w) due to boiling of refrigerant R134a. The 3D vapor bubble is immersed in the superheated liquid with no external forces such as gravity. This test is important to evaluate the implemented mass transfer occurring in the interface between the phases. As can be seen from the left to right, the vapor bubble increases its volume.



6) Conclusions:

The finite element method is a powerful and flexible way to discretize the numerical domain and to represent the fluid dynamics with accuracy. By applying the ALE technique to two-phase flows, we are able to take advantage of the best aspects of both reference frames namely Lagrangian and Eulerian. The curvature calculation approach leads to faster accurate results, compared to classical distance function calculations. This showed that the methodology proposed to simulate two-phase flows with phase change provides good accuracy to describe the interfacial forces and bubble dynamics.